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THE RELATIONSHIP BETWEEN A SUBMARINE'S MAXIMUM SPEED AND ITS EVASIVE CAPABILITY

By

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The experiences of submarine warfare from WWI and WWII have generally dictated maximum speed when designing conventional submarines. Technological development of submarine and antisubmarine weapons, however, requires examination of submarine warfare and tactics. This thesis focuses on a coastal conventional submarine's ability to survive, as a function of its maximum speed, when attacked by a light antisubmarine warfare (ASW) torpedo. It also evaluates the maximum speed with which the submarine should be equipped to ensure a specified probability of survival. The measure of effectiveness (MOE) is the probability that the submarine, operating up to maximum speed and launching only one set of countermeasures, is not caught by the torpedo.

The investigation builds on a discrete event simulation model. The systems simulated are a submarine, a light ASW torpedo, and a countermeasure system consisting of one decoy and four jammers. The results show that maximum speed of a submarine does effect the submarine's evasive performance between 12 and 18 knots. The simulated model reached a maximum probability of survival at 18 knots. That result should be regarded as a minimum since a real life system might require a higher maximum speed to reach its greatest probability of survival.

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THE RELATIONSHIP BETWEEN A SUBMARINE'S MAXIMUM SPEED AND ITS EVASIVE CAPABILITY

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EXECUTIVE SUMMARY

The demand for a high maximum speed when designing conventional submarines has primarily been dictated by the experiences of submarine warfare from WWI and WWII. Until recently this maximum speed criterion has seldom been questioned. Meanwhile, the technological development of submarine and antisubmarine weapons has required many changes in submarine warfare and tactics. These developments should also influence the demands on future submarine designs, and in particular may influence maximum submerged speed requirements.

This thesis investigates the relationship between the maximum submerged speed of a conventional coastal submarine equipped with a torpedo countermeasure system and the evasive capability of the submarine. In particular the thesis focuses on the submarine's ability to survive, as a function of its maximum speed, when attacked by a light antisubmarine warfare (ASW) torpedo. The thesis also evaluates the maximum speed with which a conventional submarine should be equipped to ensure a specified probability of survival while evading a light ASW torpedo. The measure of effectiveness (MOE) used in this thesis is the probability that the submarine, operating up to maximum speed and launching only one set of countermeasures, is not caught by the torpedo.

The investigation builds on a discrete event simulation model. The model involves the movements of the systems, the detection of targets, the logic behind the decision of attack mode or search mode for the torpedo, and the logic for execution of the evasive actions by the submarine. The systems that are simulated are a submarine, a light ASW torpedo, and a countermeasure system consisting of one decoy and four jammers. The weapons systems are based on unclassified data from open sources.

The high-speed torpedo starts its circular search for the submarine, when dropped from a ship or an aircraft. The submarine immediately executes its evasive actions after detecting the torpedo. These actions involve evasive maneuvering and deployment of countermeasure systems. The four jammers form an acoustic shield around the submarine meant to break the initial contact of the torpedo. While the decoy, which has a speed of 17 knots, seduces the torpedo to follow. Simultaneously the submarine turns away from the decoy and starts accelerating to its maximum speed.

Since the intention is to evaluate the submarine's maximum speed, the submarine is not allowed to launch a new set of countermeasures, but depends on its speed to escape the torpedo. The torpedo has a short endurance and may run out of power before it catches the submarine. If so, the submarine escapes and survives; if not, it is killed. The maximum speed is the independent variable of the experiments, and the probability of survival is measured for each maximum speed.

The results of this thesis show that maximum speed of a submarine does have an effect on the submarine's evasive performance within a specific range of speed. For the simulated model, that range is between 12 and 18 knots. The simulated model reached a maximum probability of survival at 18 knots. That result should be regarded as a minimum since a real life system might require a higher maximum speed to reach its greatest probability of survival.

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I would like to thank Professor Buss for always being available to answer any questions I raised during this process of research. Professors Sanchez and Buttrey also provided much help. Professor Sanchez's enthusiastic advice on the design of the experiment was greatly appreciated, and he served as a great inspiration. Professor Buttrey willingly gave kind help with parts of the analysis (most excellent!)

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I. INTRODUCTION

A. THE NEED FOR SPEED

The main features of the submarine have always been its capabilities to dive and to conduct attacks with powerful torpedoes from a hidden submerged position. Speed and mobility have also characterized the submarine throughout its history. Prior to the end of WWII, the submarine was by and large a surface going torpedo boat designed to dive, then stay submerged until the tactical situation allowed it to surface again. When submerged, it was powered by batteries, which had to be recharged by the submarine's diesel engines and generators when the ship returned to the surface. Thus, most WWII-era submarines were designed with a high surface speed (15-19 knots), when the diesel engines provided the energy, and a much lower submerged speed (seven to nine knots), when the battery capacity was the limiting constraint. These capabilities were also reflected in the design of the hull, a V-shaped bow allowing high surface speed. The need to surface in order to charge the batteries or to run with high speed to intercept targets made the submarine vulnerable to attacks.

When the snorkel mast was introduced in the latter part of WWII, the submarine could charge its batteries while submerged. Because the submarine did not have to surface while charging, it was designed to run at a higher submerged speed to make better tactical use of its submerged state. The German Type XXI, which entered production in 1944, was designed with a maximum submerged speed of 17.18 knots. (Miller, 1991, p.78). Conventional submarine designs since WWII have had high maximum submerged speed.

The demand for high maximum speed in post-WWII conventional submarines has primarily been dictated by the experiences of WWI and WWII. Current speed maximums range from 16 to 24 knots with design and technology constraints limiting the upper range.

Following World War II and up until the last couple of decades, few changes have been made to the design of submarines and the weapons used to attack them. Whether attacking surface ships or evading antisubmarine warfare (ASW) platforms, high speed

has generally been crucial for the submarine to succeed in its mission. The general scenario determining a specific top speed for a submarine was as follows:

To carry out an attack, the submarine first penetrated the screen of escorts around the target and then moved into a firing position. This position normally provided a torpedo track of between 1,000 and 3,000 meters. To reach a firing position, the submarine often needed to use its maximum speed to sprint into a favorable position close to the target's course line or mean line of approach (MLA). Thus the submarine's required maximum speed had to exceed the target's speed, which was approximately 15 knots for a convoy. After the attack, the submarine again had to use high speed to clear the datum (the last known position the enemy had on the submarine) it had just created and to evade the antisubmarine escorts. Because of flow noise around the hull, the performance of the surface ship's search-and-attack sonar was severely degraded when the ship's speed exceeded 15 to 16 knots.

Today, technological developments of submarine and antisubmarine warfare have changed the situation. The submarine's modern anti-surface warfare (ASuW) torpedoes are both wire-guided and homing, and they have increased tactical range of 15,000 meters or more. This increased torpedo range relaxes the former demand for the submarine to quickly achieve a firing position close to the target's track, so high speed in this phase of the attack is no longer needed.

The threat against the submarine has also changed in nature. During an attack on an escorted target, the main threat used to be the first generations of ASW torpedoes or depth charges either dropped directly from the escorts or mortared out to a specific range from the ship. Today the most dangerous threat to a submarine, both during an attack and in other situations, is a modern light torpedo dropped from a ship's helicopters or from maritime patrol aircraft (MPA).

The light ASW torpedo is a sophisticated weapon that homes in on the submarine with a high speed of between 32 and 50 knots. A conventional submarine is not able to outrun a torpedo dropped within some range close to it. The submarine, however, might make use of its stealth capacities to avoid detection from the torpedo's sonar or, if detected, to try to break contact by different countermeasures and clear the datum by

sprinting away. A light torpedo normally has short endurance. By the time it manages to regain contact, the submarine could be out of its range. Thus, the submarine needs to have a maximum speed high enough to open the distance from the last datum held by the searching torpedo so that the torpedo is unable to catch the submarine.

Both in the development of staff requirements for new submarine designs and in the evolution of evasive tactics, it is of great interest in the submarine community to determine the consequences of the submarine's maximum speed on its evasive capabilities. This thesis addresses maximum speed and its impact on modern submarine design.

B. PROBLEM DESCRIPTION

1. Problem Statement

The questions addressed by this thesis concern the evasive performance and maximum speed of a conventional submarine equipped with a torpedo countermeasure system when attacked by a modern light ASW torpedo dropped by an aircraft. Specifically:

- What is the effect of a conventional submarine's maximum speed on its evasive performance when attacked by a modern light ASW torpedo?

- What should be the maximum speed of a conventional coastal submarine equipped with a torpedo countermeasure system to ensure a specified probability of survival while evading a light ASW torpedo?

2. Methodology

To define this problem properly, it is necessary to describe the capabilities and performance limits of <u>conventional submarines</u> and <u>light ASW torpedoes</u>, and of the possible <u>torpedo-countermeasure systems</u>. It is also important to understand the evasive actions taken by a submarine, and the operating scenario for the submarine, torpedoes, and countermeasure systems. The following paragraphs discuss evasive actions and operating scenarios, while the next section provides an overview of the systems.

Evasive actions taken by a submarine consist of the following phases or elements in sequential order:

- *Avoid detection.* In this phase the submarine takes advantage of its low signatures (both its self-generated noise radiation and its target echo strength), and the oceanographic conditions in order to remain undetected.

- *Break contact.* If detected it is necessary to take evasive actions to break the contact. This can be done by change of speed, course, or depth, or by deploying some sort of torpedo countermeasure device. Most often a combination of these actions is carried out. The countermeasures can be decoys that transmit the same sonar pulses as those transmitted from the torpedo, or simply just air bubbles released by the submarine. The countermeasures can also be powerful noise generators made to screen the submarine from the torpedo.

- *Clear the datum.* If the submarine is successful in breaking the contact, it is of importance to clear its position last known to the enemy.

These evasive phases are the same whether dodging a delivery platform or an incoming torpedo. This thesis considers only situations in which the submarine evades a light torpedo.

The geometry of this scenario is different in each case. The scenario depends on the initial distance between the submarine and the torpedo, and the relative bearing of the torpedo to the submarine. Other variables are the relative courses of the countermeasure devices deployed from the submarine.

This thesis focuses on the probability that the submarine escapes the torpedo. That is the probability that it manages to run into a safe position by diverting the torpedo with its deployed countermeasures and using its high speed. A safe position is one where the torpedo can no longer reach the submarine because of the torpedo's limited endurance. This thesis focuses on the submarine's speed required to achieve a safe position, and does not evaluate the more complex total probability of submarine survival,

which is a function of the torpedo's probability of hit (P(hit)) and probability of inflicting mortal damage given it hits (P(mortal damage)).

3. General System Descriptions

a. Description of a Conventional Submarine

The small conventional submarine (known by the designator SSC) has a displacement of approximately 500-1,500 tons and is mainly designed for coastal operations. It can also carry out blue water operations (for which the large ocean going conventional submarine (known by the designator SSK) is designed) within its range and endurance limits.[1] The small size benefits its acoustic target echo strength (TES) signature, which tends to be lower than the TES of SSKs and nuclear attack submarines.

Conventional submarines have maximum submerged speeds of 16 to 24 knots, and very low acoustic signatures. Their maximum speed is much lower than that of nuclear-propelled submarines. They also have very short endurance at maximum speed. Endurance depends on the battery capacity when the top speed run starts. Quite often the submarine is unable to maintain top speed for more than 15 to 30 minutes.

Conventional submarines are equipped with a diesel electrical propulsion system consisting of a main electrical motor that turns the propeller shaft. The electrical motor is powered by the battery package, which occupies a considerable amount of space onboard. The batteries are charged by generators powered by the diesel engines, which again can be run while submerged at periscope depth (PD) by the use of a snorkel mast. New submarine designs also plan the installation of an air independent propulsion system which, without restricting the submarine's operating depth, can charge the batteries without snorkeling. This new system would be capable of instantaneously providing the main electrical motor with the power needed for lower speeds. Such a design would help the submarine maintain a high battery capacity at any time, improving the endurance of a maximum speed run.

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[1] A small conventional submarine designed to operate in coastal waters is normally given the designator SSC, while larger conventional submarines designed to operate in open ocean (blue water) is a SSK. These designations are related to the range and endurance of the two categories of submarines, where the SSK has the longest range and longest endurance of the two. These designations are also related to the capabilities of the submarines. The SSK often has better ASW capability than the SSC, while the SSC might certainly be ASW capable but is mainly both designed for and tasked to execute ASuW operations.

Because of the small size of these submarines, conventional submarines have limited space for torpedo storage. The submarines in some cases may not be equipped with a torpedo storage room at all, instead carrying all their torpedoes in the torpedo tubes.

Because of the submarine's design restrictions, high submerged speed is a costly demand. The maximum speed is one of the elements that drives the design of a submarine. It affects the size and numbers of batteries, which may possibly increase the size of the submarine or take up valuable interior space. The batteries in turn affect the size of the diesel engines, the generators, and the snorkel system. The maximum speed also affects the size of the electrical propulsion motor. Since size of a submarine has a negative impact on its target echo strength (TES) signature, a larger submarine is in general less stealthy than a smaller one.

The main task of the SSC is anti-surface warfare (ASuW). With long-range torpedoes, the submarine can carry out an attack on surface ships from distances well outside the surface ships' weapon ranges, except when the surface ships carry organic ASW helicopters or fixed wing aircraft.

b. Description of a Light ASW Torpedo

Modern light ASW torpedoes have a high speed of 32 to 50 knots, a fairly small warhead with approximately 30 to 50 kilograms of high explosives, and an engine compartment designed to attain high speed quickly and to maintain the speed for only six to ten minutes. The torpedo is normally equipped with a high frequency sonar with low power, limiting its range to 700 to 2,000 meters.

c. Description of a Torpedo Countermeasure System

There are a number of expendable torpedo countermeasure systems available on the market today. Most systems consist of one decoy launched from the submarine's signal ejector. The decoys are designed to seduce the incoming torpedo and cause it to break contact with the submarine. Once launched, the decoy operates independently of the launch platform and holds station at its launched depth or at a pre-selected depth. There are also similar systems that consist of a large self-propelled decoy

launched from the submarine's torpedo tubes (e.g., Russian MG-74ME). This is a sophisticated system, but has the disadvantage that it occupies a torpedo tube and displaces a torpedo.

More sophisticated systems consist of several units that are launched. One or more of these are decoys while the others are jammers, whose role is to screen the radiated noise from the submarine as well as the submarine's echo from the torpedo's active sonar. The decoy units may also be self-propelled and move away from the submarine. These systems are launched from canisters outside of the submarine's pressure hull, considerably decreasing the reaction time.

Some of these systems are automatically launched when the submarine's torpedo warning system detects a torpedo. Other systems require the order from the submarine's Commanding Officer (CO) or from the Officer on Watch.

This chapter described the historical need for high maximum speed. Based on the development of ASW and ASuW, both weapons and tactics, this chapter sets up the questions of the development of the submarine design of today, and in particular the demand for speed. This chapter described the weapon systems that are of interest in general. The next chapter describes these weapon systems in detail as they are used in this thesis.

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II. DESCRIPTION OF THE SCENARIO

This chapter describes the measure of effectiveness to be used, the scenario of interest, the three different weapon systems, and how they interact in this scenario. The three main weapon systems, the submarine, the torpedo, and the torpedo countermeasure system, are all generic systems. This thesis does not contain any classified information.

The scenario consists of one submarine and an incoming light torpedo dropped at a position randomly chosen within a radius of 2000 meters and within a relative bearing between 0 and 360 degrees from the submarine. When the submarine detects the torpedo, it conducts a preset evasive maneuver after a given time delay, and launches the countermeasure system, consisting of one decoy and four jammers. The countermeasure units are self-propelled. The decoy moves away from the submarine, while the noisemakers deploy in a pattern around the submarine to shield it from the torpedo's sonar.

This chapter develops the measure of effectiveness (MOE) which is then used to evaluate the behavior of the weapon systems and their interactions under various scenarios. The MOEs are developed with respect to the problem statement (ref Chapter I) which emphasizes the evasive performance of the submarine as a function of its maximum speed. After describing the measures of effectiveness used, this chapter describes the systems and the geometry of the scenario in more detail.

A. MEASURE OF EFFECTIVENESS

The primary measure of effectiveness (MOE) is the probability that the submarine, operating up to maximum speed and launching only one set of countermeasures, is not caught by the incoming torpedo. Perhaps the submarine manages to outrun the attaching torpedo, and the torpedo thereafter runs out of power before it can catch up with the submarine. The submarine might also be able to get outside the torpedo's detection range before the torpedo finishes investigating the decoy. In these cases the survival of the submarine is a function of the synergy between the countermeasure system and the evasive run of the submarine, where the maximum speed of the submarine is the only independent variable of the trials.

This MOE is chosen to ensure that the submarine's maximum speed is evaluated, not the effectiveness of the submarine's torpedo countermeasure system or the effectiveness of the torpedo. If, for instance, the submarine launches several sets of countermeasure systems, it might manage to keep the torpedo at a safe distance without the use of speed at all. In these cases, it is not the performance of the submarine that is measured but rather that of the countermeasure system.

Another MOE that could be considered is the probability that the submarine is killed by the incoming torpedo. This MOE is quite complicated and involves other variables not necessarily related to the speed of the submarine, such as the effectiveness of the torpedo's warhead. Consequently, this thesis will use the first MOE.

Although the MOE focuses on the catch or the escape of the submarine, there might be reference to the kill or the survival of the submarine in this thesis. The probabilities of kill or survival are understood as the probabilities of catch or escape of the submarine.

B. DESCRIPTION OF THE SYSTEMS

This section contains a detailed description of each of the weapon systems and their subsystems. It also describes the geometry of the scenario, and how each system interacts in detail.

This is an unclassified thesis, and all warfare systems used are generic. They are built on existing systems though, with data from open sources like *Jane's Fighting Ships* or *Jane's Underwater Warfare Systems.* These data are primarily performance characteristics such as speed and range, and have not provided information of the systems' performance and actions taken in the scenario of interest. In cases where the action or reaction performed by each of the systems is of importance for the scenario and the model, the characteristics have been developed for the purpose of this work. The performance characteristics are described in more detail later in this chapter. Note that the actions taken in similar situations by existing systems might be different than the actions taken by the generic systems of this thesis.

1. The Torpedo

The torpedo used in this model is a lightweight anti-submarine torpedo, which can be fired from either a surface ship or from a helicopter or maritime patrol aircraft (MPA). The torpedo has standard dimensions for lightweight torpedoes; it is 2.6 meters long with a diameter of 0.32 meters. It has a speed of 40 kt (20.58 meter per second) and a turn-radius of 65 meters. Its endurance is eight minutes. By comparison the British-produced Sting Ray torpedo has a speed of 45 kt and the US-produced Mk 46 a speed of 40 kt. The endurance for both of these two torpedoes is approximately 8 minutes *(Jane's Underwater Warfare Systems*, pp. 248, 249, 251, 252). A turn-radius of 65 meters is assumed. The torpedo is equipped with a search and attack sonar with an effective detection range of 1500 meters. The sonar has a search sector of 45 degrees to each side of the torpedo's centerline.

The torpedo is dropped within 1500 meters from its target, the submarine. It is preset to search in a circle until it makes contact with a target, either a submarine or a decoy. In the worst case the torpedo might not make contact at all, and circles in this position until the end of its life. In most cases in this study though, the torpedo makes contact with either the submarine or the decoy.

The torpedo chooses the target that has the highest acoustic target strength (TES) and attacks it. If the chosen target is the decoy, the torpedo at some point reclassifies its target as a non-submarine because its warhead does not receive the expected ignition criteria. (Either the torpedo senses the lack of an expected magnetic signature from its target, or misses the expected force of an impact.) Some torpedoes may detonate when hitting a decoy, but that is not a situation considered in this thesis. If the decoy starts the ignition process in the torpedo, the model would not measure the performance of the submarine and the value of its maximum speed, but the efficiency of the countermeasure system instead. The countermeasure system's role is to seduce the torpedo and screen the submarine so that the submarine can clear the datum by the use of its speed before the torpedo starts chasing it.

When the torpedo has reclassified the decoy correctly, it either starts running after the submarine, if it is in contact, or performs a new search by going into circles. It is thus

capable of searching the area behind it again, which it passed while it had locked on and chased the decoy. If the submarine now is outside the protection given by the noisemakers and still within the range of the torpedo's sensor, the torpedo should be able to gain contact, and this time attack its proper target. It is now a race between the relatively slow submarine and the much faster torpedo. At this moment when the torpedo starts its final chase, it is only the distance between the two and the remaining endurance of the torpedo that determine the outcome of the game.

2. The Submarine

The submarine is a small conventional submarine, designed for operations in coastal and shallow waters. It has a displacement of 1000 tons, a turn-radius of 120 meters and an acceleration of 0.05 meters per second squared. The maximum speed of the submarine is the independent variable in this model and has been varied between 12 and 24 kt. The submarine is equipped with passive search sonars and a sonar-warning system designed to detect active sonar emissions from other platforms. The submarine can, with these sensors, theoretically detect an active sonar at twice the distance as the active sonar from the torpedo can detect the submarine.

When a torpedo is detected, the submarine begins a set of evasive actions. It deploys the decoy and a pair of jammers, and then start its evasive maneuver. To get as far away from the decoy as possible it starts accelerating to maximum speed, and turns towards a course approximately reciprocal to the decoy's course.

3. The Torpedo Countermeasure System

The torpedo countermeasure system in this model consists of one decoy and four jammers placed outside of the submarine's pressure hull (for instance in the casing or in the sail). This generic torpedo countermeasure systems are similar to the German TAU-2000 and the Italian C303/310 torpedo countermeasure systems (*Jane's Underwater Warfare Systems*, pp. 169-171). The four jammers are shot in pairs, with one jammer on each side of the submarine, and with an interval of 14 seconds between the two pairs. They are self-propelled with a short range. At a relative course 30 degrees off the submarine's course to each side, they swim 40 meters out to a position where they stop and become stationary while emitting the acoustic noise. The four jammers then form a

cluster of noise around the submarine in the crucial first 25 - 30 seconds (Figure 1), so that the torpedo, if already in contact with the submarine, might lose contact.

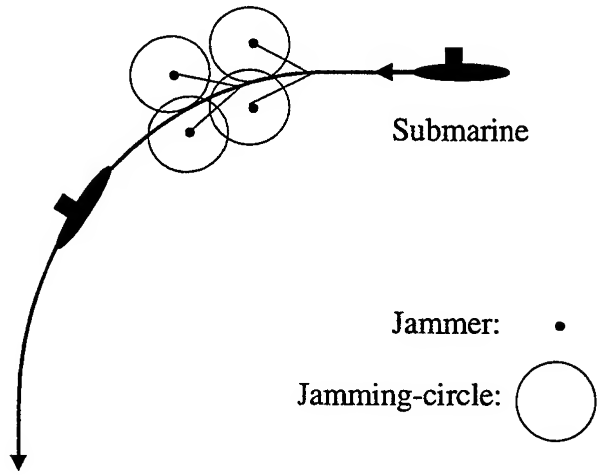

Figure 1: Example of how jammers are deployed around the submarine's track.

The torpedo might then make contact with the decoy. The decoy is also self-propelled with a speed of 17 kt and a range of 10000 meters. It responds to the sonar transmissions from the torpedo and returns a signal that is meant to sound like the echo from a submarine. The decoy is ordered on a course perpendicular to the bearing of the torpedo. While the decoy attracts the torpedo towards itself, the submarine runs at maximum speed in the opposite direction. The submarine attempts to keep the existing cluster of noisemakers, still stationed in its deployed position, between itself, and the decoy and torpedo.

4. The Geometry of the Scenario

Each scenario's geometry depends on the relative bearing of the torpedo to the submarine. More specifically, the bearing is established at the time the submarine detects torpedo. At that moment, the submarine must react quickly to the incoming threat, and conducts necessary counteractions as soon as possible. Based on the bearing to the torpedo, the submarine calculates the firing course of its decoy and its own evasive

maneuver. In general there are four different situations, one for each of the quadrants around the submarine from which the torpedo can come. For each of these situations the submarine reacts differently as to which way it turns and where it sends its decoy.

By using the decoy, the submarine tries to keep the torpedo as far away from itself as possible. That is achieved by sending the decoy on to a course perpendicular to the bearing of the torpedo, and then turning the submarine towards a course reciprocal to the decoy's course. With respect to bringing the submarine away from its initial position, the turn itself does not contribute as much as a linear motion would. For this reason, and also because a turn decreases the submarine's acceleration, it is of importance for the submarine not to turn more than necessary. In order to never turn more than 90 degrees, the decoy is always shot on a course into the two aft quadrants of the submarine.

In all of the scenarios, the initial velocity of the submarine has been defined with a direction of (-1, 0); the areas initially related to the forward part of the submarine are the second and the third quadrants of the circle, respectively related to the starboard and port sides of the submarine. Similarly, the areas aft of the submarine are related to the first and the fourth quadrants of the circle. The first quadrant is on the starboard side and the fourth on the port side.

a. Incoming Torpedo in Quadrant II

When the bearing of the torpedo is to the starboard side of the submarine from relatively straight ahead to 90 degrees starboard, the decoy is fired into Quadrant I on a course perpendicular to the torpedo's bearing. The submarine accelerates and turns port to a course in the third quadrant where it might keep the decoy straight aft of itself. (ref Figure 2).

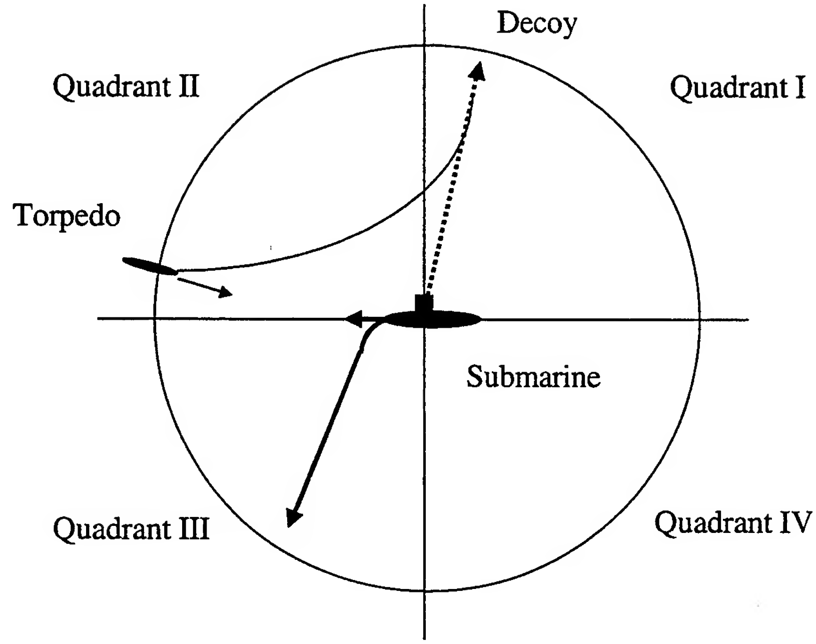

Figure 2: Example of a scenario where the torpedo comes from the 2^{nd} quadrant

b. Incoming Torpedo in Quadrant III

The submarine's reaction to an incoming torpedo from the third quadrant is similar to its reaction in the second quadrant scenario. In this case the submarine fires the decoy into the fourth quadrant, perpendicular to the bearing of the torpedo. The submarine evades by accelerating to maximum speed and turns to starboard into the second quadrant. (ref Figure 3).

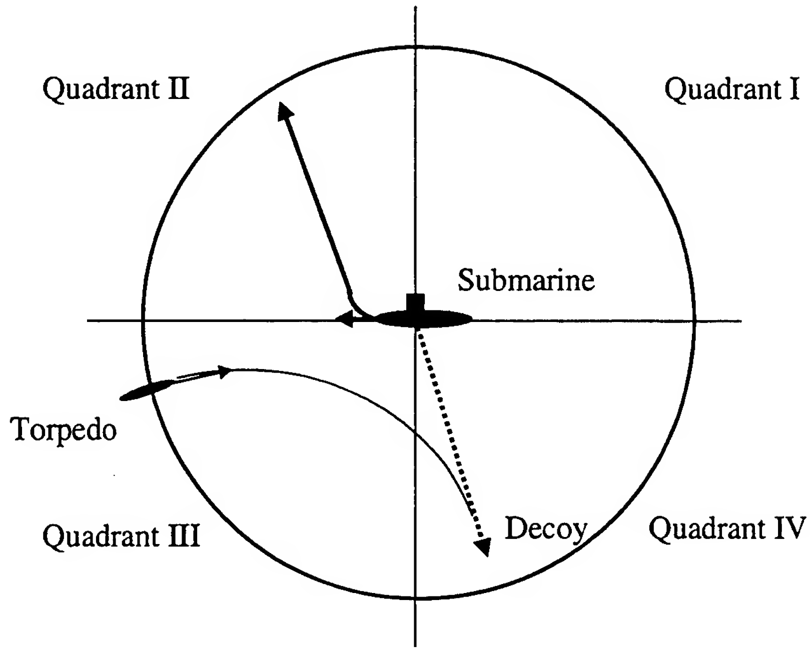

Figure 3: Example of a scenario where the torpedo comes from the 3^{rd} quadrant

c. *Incoming Torpedo in Quadrant I*

When the bearing at the time of detection from the submarine to the torpedo is in the first quadrant, the decoy is again fired into the fourth quadrant, and the submarine evades to starboard into the second quadrant. (ref Figure 4).

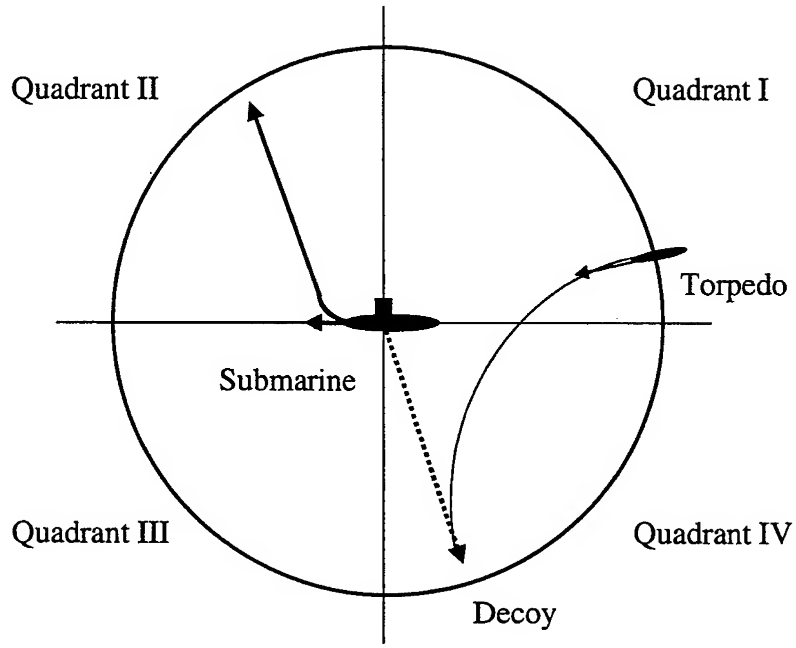

Figure 4: Example of a scenario where the torpedo comes from the 1st quadrant

d. Incoming Torpedo in Quadrant IV

When the bearing at the time of detection from the submarine to the torpedo is in the fourth quadrant, the decoy is fired into the first quadrant, and the submarine evades to port into the third quadrant. (ref Figure 5).

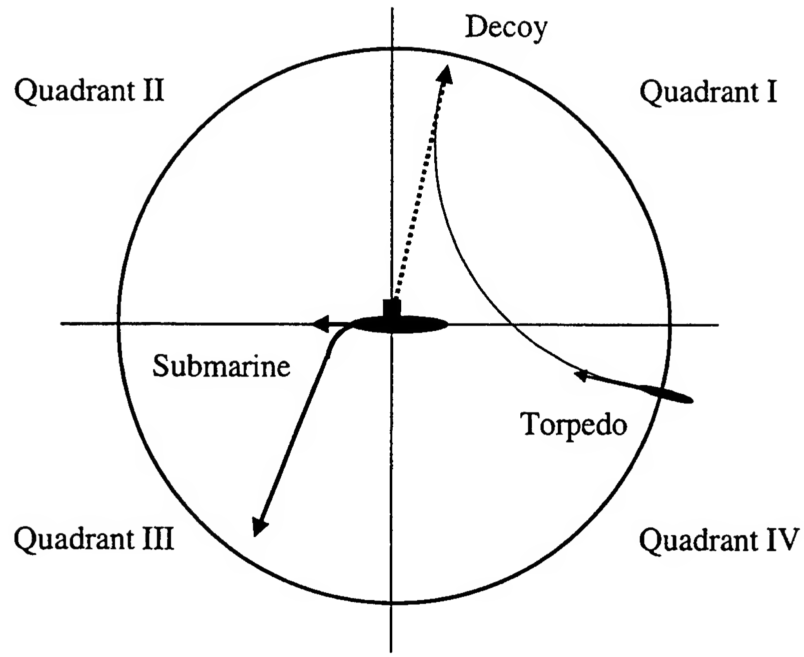

Figure 5: Example of a scenario where the torpedo comes from the 4^{th} quadrant

Ideally, if the submarine's turn-radius is close to zero, the submarine should turn to a course that is the torpedo bearing +/- 90 degrees. Since the submarine has a relatively large turn radius in this scenario, 120 meters, the submarine would in some cases have made a turn that is too large. In the worst cases, when the relative bearing to the torpedo is nearly straight-ahead or nearly straight aft, the decoy is shot on a course nearly perpendicular to the submarine's course, and the submarine correspondingly must make a large turn. Those cases should be seen as the most extreme, and the geometry shows that the submarine should not have to turn as much as 90 degrees in order to keep the decoy and the torpedo straight aft. (ref Figure 6).

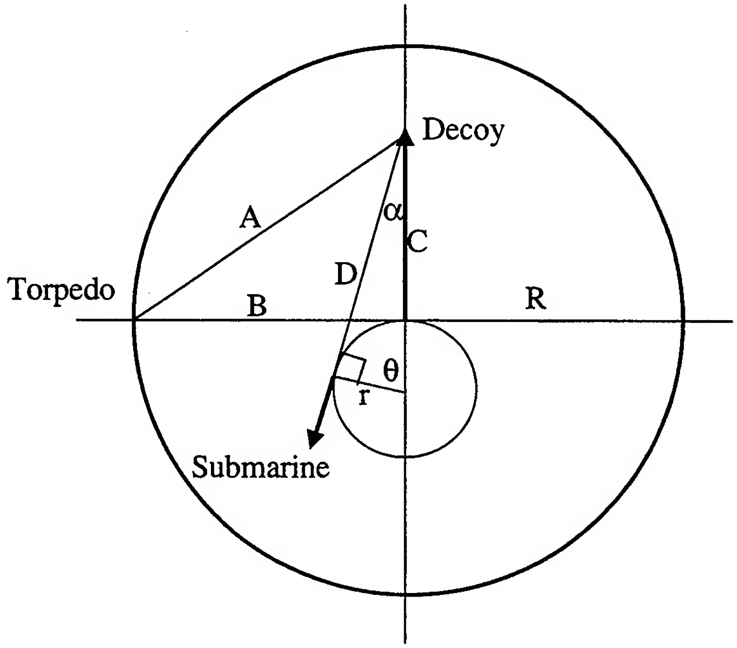

Figure 6: The submarine's turn-angle θ

The geometry also depends on how far from the submarine the torpedo is when the submarine's counteractions start. If the torpedo is detected while it is far from the submarine, it gives the decoy more time to move away from the submarine before it is caught by the torpedo than if the torpedo is detected close to the submarine. In all scenarios where the decoy's course is perpendicular to the submarine's initial course, the magnitude of the submarine's turn depends on the distance B to the torpedo at the start of the torpedo counter actions, the submarine's turn radius r, the torpedo speed v_t and the decoy speed v_d. The time t is the time when the torpedo recognizes the decoy and starts a new search for the submarine again. The time t gives the start position C of the torpedo's new search, which is the position the submarine would want to keep straight aft when running away.

$$t = \sqrt{\frac{B^2}{v_t^2 - v_d^2}}$$

$$C = v_d t$$

The submarine's turn is therefore a function of the distance C to the position where the torpedo starts a new search, and the submarine's turn radius r.

$$\theta = \cos^{-1}\left(\frac{r}{C+r}\right)$$

This is the exact magnitude of the turn the submarine should conduct in the cases where decoys are launched on courses perpendicular to the courses of the submarines, instead of the first calculation which was a 90 degree turn. θ is measured from the bow of the submarine (-1, 0). A negative valued θ describes a starboard turn, and a positive valued θ describes a port turn.

For cases where the bearing of the torpedo (β_t), which is measured from (1, 0), is not straight ahead or straight aft, the above expression is not valid. If the bearing of the torpedo is in Quadrant I or II ($0° < \beta_t \leq 180°$) the following approximation is used:

$$\theta = ((\beta_t + 90) - 180) \cdot \left(\frac{\cos^{-1}\left(\frac{r}{C+r}\right)}{90}\right)$$

The first part of this expression is the turn the submarine would have done if its turn radius had been close to zero. The second part decreases the turn in order to incorporate the magnitude of the turn radius.

If the bearing of the torpedo is in Quadrant III or IV ($180° < \beta_t \leq 360°$) the following approximation is used instead:

$$\theta = ((\beta_t - 90) - 180) \cdot \left(\frac{\cos^{-1}\left(\frac{r}{C+r}\right)}{90}\right)$$

Since the submarine's initial direction is defined to be (-1,0), its initial course is also 180 degrees. The above approximations simplify the calculations of the

magnitude and direction of the turn for all the scenarios, and do not introduce significant errors for the MOE estimated.

This chapter has described the scenario and the systems. The next chapter presents modeling of the systems for the simulation.

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III. DESCRIPTION OF THE MODEL

This chapter describes the analytic model integrating each of the weapon systems and the interaction among the weapons systems. The model is created to most closely approximate the systems and their behavior as described in Chapter II. This chapter discusses assumptions and approximations of the model. The next chapter discusses the implementation of the model and presents the computer model, a discrete-event simulation.

A. THE TORPEDO MODEL

The torpedo is modeled with two modes, search mode and attack mode, supported by four major features. The first of these features is the search pattern, which is used when the torpedo lacks contacts to lock onto and attack. The second feature is the target selection logic. The third is the attacking run, and the last is the classification of a non-target, such as a decoy.

1. The Search Pattern

The torpedo is dropped from chosen positions within its sonar range of 1500 meters of the submarine. To orient the torpedo, its initial direction is headed towards the initial position of the submarine.

When the torpedo is dropped, it immediately begins to search. The search pattern continues when the torpedo loses the contacts it made or when it correctly classifies the decoy it has chased and begins to locate its real target, the submarine. Since the torpedo's sonar is limited to a sector of 45 degrees to each side of the centerline of the torpedo, the search is conducted by circling. The sonar covers the area within a radius of the sonar range plus the torpedo's turn radius r_t. To approximate the torpedo's circling search, the model uses a hexagon (ref Figure 7). As shown below, this assumption does not introduce significant errors for the MOE estimated.

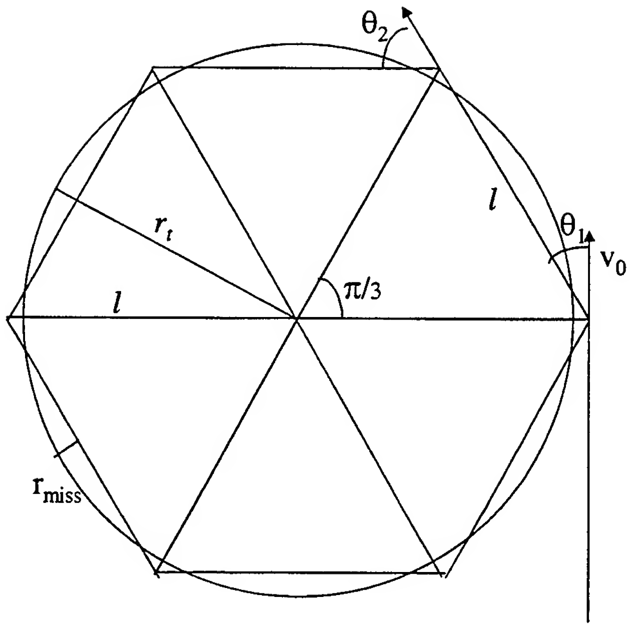

Figure 7: The hexagon path of the torpedo search pattern.

The model rotates the torpedo through the six vertices of the hexagon. The hexagon path approximates the circular path fairly accurately; an adjustment makes the simulated torpedo take the same lap time as it would have in a perfect circle. This is achieved by letting each leg l in the hexagon be a bit longer than the original r_t.

$$l = \frac{\pi}{3} r_t \approx 1.047 r_t$$

Using the hexagon as an approximation for the circular sweep causes the torpedo to move slightly outside the original circle at each of the vertices. Note, however, that the torpedo moves mostly inside the circle at each leg. The missing part of the radius is r_{miss}:

$$r_{miss} = \left(1 - \frac{\pi\sqrt{3}}{6}\right) r_t \approx 0.093 r_t$$

When the search is initiated, the torpedo makes a 30-degree (θ_1) turn to port onto the first leg l of the hexagon. The next turn (θ_2), and all the subsequent turns in the

search will be 60-degree turns to port. Until the torpedo makes acoustic contact with a target, it continues this search pattern.

The area covered by the torpedo sensor conducting the hexagonal search (A_h) relative to the area covered by a perfect circle search (A_s), depends on the range of the sensor perpendicular to the torpedo's centerline (R_p) and of the radius of the circle r_t. The relationship between these two areas is expressed by the equation:

$$\frac{A_h}{A_s} = \frac{3\left(\frac{\pi}{2\sqrt{3}} r_t + R_p\right)\left(\frac{\pi}{3} r_t + \frac{2}{\sqrt{3}} R_p\right)}{\pi\left(r_t + R_p\right)^2}$$

If the radius r_t equals 50 meters and the perpendicular range (R_p) of the sonar is close to zero, the value of this relationship is approximately 0.91. In this case the hexagonal search model covers a search area about 9% smaller than a circle search would cover.

With an increasing sensor range, the relationship quickly increases to a value greater than one. For a realistic range of approximately 1000 meters to each side of the torpedo (R_p), the value of this relationship is about 1.09. The maximum sonar range used in this model is 1500 meters, which for a +/- 45-degree sonar sector has a side range of $R_p = 1500\sqrt{2}/2$. In this case, the relationship between A_h and A_s is 1.091. This means that the area covered by the hexagonal search model, with sensor coverage, is at most 9.1% larger than the sensor coverage for a search conducted in a perfect circle. This hexagonal approximation to the search is regarded as a sufficient model for the torpedo's search pattern.

2. The Target Selection Logic

The torpedo's sonar is implemented in the model by a constant-rate sensor. A constant rate sensor has two parameters; the maximum range and the detection rate. When a target enters the sensor's range the time to detection is exponentially distributed with a mean value of the inverse of the sensor's detection rate. If the target leaves the sensor's range before the detection time, the detection is cancelled. Note that in reality, a torpedo has a sensor-sector of +/- 45 degrees from the centerline of the torpedo, and

should not make contact with targets outside its sensor-sector. Below it is explained how this sector is implemented.

In the model, the torpedo detects sonar emissions and stores detected contacts in a detection list that the torpedo brain "logic" evaluates. Possible contacts can be submarines, decoys, or one of the jammers. Jammers are not considered targets; at each sonar "ping," contacts classified as jammers are copied into a "jammer list," and all other contacts are copied to a possible target list.

Contacts may be eliminated from the target list in two situations. First, the bearing of each of the contacts on the target list is checked to see if they are within the sector of the torpedo's sensor. Targets not within the torpedo's sector are removed from the target list.

The positions of possible targets are then compared with the positions of each of the jammers from the jammer list. These noisemakers are modeled as an ideal form for jammers. The jammers are assumed to be 100% efficient, and a target located behind the circle formed by the jammer and its jamming radius will not be detected. Targets located behind the circle of the jammer and its radius are removed from the target list.

When a target is removed from the target list it continues to exist on the contact list, and is available for evaluation at the next simulated sonar emission. The torpedo and the contacts will then have moved relative to each other, and a contact that had been removed from the target list is again a potential target.

Once the target list is accepted, the torpedo begins its attack on a target. If only one contact remains on the target list, the torpedo's choice is simple – the torpedo begins attacking the target. If there are two contacts on the target list, a submarine and a decoy, the torpedo automatically chooses the decoy. This assumption reflects how a decoy is meant to work tactically. This is also an ideal way of implementing the target echo strength (TES) for the decoy and the submarine, which are modeled as high and low, respectively. Thus, the model assumes that if the torpedo initially begins to chase the submarine but receives target criteria to misidentify the decoy at a later sonar emission, it switches focus to the decoy and chases it instead. This allows the decoy to stop the torpedo's attack on the submarine, giving the submarine a chance to evade.

3. The Chase

When the torpedo begins chasing its target, the path of the torpedo is updated after each sonar emission. Each sonar ping provides the torpedo with the distance and the bearing to the target, so that the torpedo can guide itself step by step towards the target. The torpedo does not take the shortest route to intercept the target, but instead follows a curved line, with a slope increasing towards the point of interception. This path might be called a "dog-curve," because it resembles the path a dog follows during a chase. (Dogs are obviously not good at calculating the point of interception!)

4. The Classification of a Target or a Non-Target

When the torpedo has caught the decoy it quickly reclassifies it correctly, and begins a new search for the submarine. The model prohibits the torpedo from making contact with the decoy again, because that scenario shifts focus away from the objective of the thesis. (The model might measure the effectiveness of the torpedo countermeasure system instead of the submarine's maximum speed's impact on the survivability of the submarine.)

To be able to simulate the model, additional assumptions about detection of contacts are made. The first is that the model allows the torpedo to reclassify the decoy when the two are close enough together to provide the torpedo with indications that its ignition mechanism should have ignited. Ignition occurs when the torpedo receives the correct magnetic signature from the target or, when the target is a submarine, the torpedo receives the correct force from the impact. Since the decoy gives neither, the torpedo is able to reclassify the decoy as a non-submarine.

In the model the torpedo kills a target at the time the sensor gives the information that the distance to the target is closer than one meter. When the torpedo kills the target, its state becomes *undetectable*. This ensures that the torpedo does not make contact with the same target again, no matter whether the target was a decoy or a submarine. If the killed target was a decoy (which is now undetectable), the torpedo attacks the next target on its contact list; if it has a contact, it should be the submarine. If it does not have any contact on the contact list or if the listed contacts are either outside its sensor-sector or shielded by one of the jammers, the torpedo again starts on its search pattern.

B. THE SUBMARINE MODEL

To model the submarine, assumptions must be made about velocity, speed, turns, and factors affecting its movement. On each simulation run, the submarine moves in a initial direction defined to be (-1, 0). The initial speed is a variable that can be changed in the program, but is in this thesis kept at the same value for all the experimental runs. The initial speed is set at 5 kt. The maximum speed to which the submarine can accelerate is the independent variable in the model, and varies from 12 and 25 knots for each set of simulations.

The two main features of the submarine model are both related to its evasive actions. The first is the initialization of the torpedo countermeasures, and the second is the evasion by the submarine itself. Both of these evasive actions are executed at a randomly chosen delayed time, after the submarine has detected the torpedo. The delay time is chosen to simulate a reaction time from the submarine's Commanding Officer or the Officer on Watch. As with the torpedo, a constant-rate sensor implements the submarine's sensors. The submarine's sonar is passive and therefore detects the torpedo's active sonar emission. The model assumes the detection range of the submarine's sensor is twice the range of the torpedo's sensor range.

The model initializes the submarine's evasive actions after it has calculated in which of the quadrants the torpedo is located (ref Section II.B.4). The submarine then chooses to send the decoy to either Quadrant I or IV, and turns the submarine into Quadrant III or II, respectively.

1. The Execution of the Torpedo Countermeasures

When the evasive actions are executed, the decoy and the first pair of jammers are the first elements of the torpedo countermeasure system to be launched from the submarine. The submarine calculates the course of the decoy on the basis of the bearing of the torpedo before launching the decoy. Fourteen seconds later the next pair of jammers is launched. Each pair of jammers launched consists of one jammer on each side of the submarine.

2. The Evasion by the Submarine

The submarine is modeled so that it can accelerate and turn at the same time. The acceleration is designed with a constant magnitude, which is executed as an on-or-off basis in the model. The turn function in the model is based on a fixed-turn radius.

When the evasive action is executed, the submarine begins to accelerate and turn immediately. In reality, a turn causes an extra drag on the submarine; thus the model slows the acceleration by decreasing it by a constant factor of 0.9 throughout the turn. If the submarine reaches maximum speed during the turn, it finishes the turn with constant (maximum) speed. In most cases though, the turn is finished before the submarine has reached maximum speed; when the turn is complete, the submarine continues to accelerate with maximum acceleration until maximum speed is reached. After both the turn and the acceleration have been completed, the submarine continues straight ahead on one course at maximum speed. It continues until the torpedo kills it or the torpedo reaches the end of its endurance. At this point the simulation ends.

C. THE TORPEDO COUNTERMEASURE MODEL

The two basic elements of the torpedo countermeasure system, the decoy and the jammers, are modeled so that the submarine executes each one at the appropriate time. The behavior and the properties of the jammers and the decoy are modeled in a manner that is as realistic as possible.

1. The Decoy

The decoy is modeled so that it is launched on a course perpendicular to the bearing to the incoming torpedo (ref Chapter II). The model allows the decoy to move with a constant velocity of 17 knots to a position 10,000 meters from the submarine. The distance of 10,000 meters is chosen to ensure that the decoy does not stop before the torpedo has had enough time to investigate it. The decoy is undetectable as long as it has the same position as the submarine, but the moment it leaves its platform it becomes detectable. When the torpedo has caught and killed the decoy, the decoy continues to exist in the model, but is no longer detectable. It does not interfere with the torpedo's next task of detecting and attacking the submarine.

2. The Jammers

Depending on the position of the jammer, starboard or port side of the submarine, the submarine orders the jammer to move to a position 40 meters away from the firing position, 30 degrees off the submarine's course to its chosen side. Each jammer is modeled with a speed of 8 knots, fast enough to get it in front of the submarine. Each of the jammers is equipped with a jamming radius set to 20 meters. The jamming radius is copied and used by the torpedo when it checks to see if the jammer shields the target. The jammers are modeled to take position in front of and on each side of the submarine, creating a protective screen around the submarine.

This chapter described how the scenario and the weapon systems are modeled. The next chapter discusses the implementation of the model as a simulation.

IV. DESCRIPTION OF THE SIMULATION PROGRAM

This chapter describes how the models of the weapon systems and their behavior described in the previous chapter are implemented in Java programming code. It presents the main subroutine called a "class" in Java, and the most important classes that form the simulation model. Main class instantiates ("calls into being" and assigns initial parameter values to) all systems and executes the simulation model. Other classes incorporate the features of each of the systems and provide the structure to model the interaction between the systems. To implement the simulation model, the Simkit simulation package created by Professor Arnold Buss at the Naval Postgraduate School (NPS) and Kirk Stork, a graduate of NPS, has been used (ref Stork, 1996).

A. THE MAIN CLASS

To execute the discrete event simulation model, the main class called *SubExperiment* is used. All variables for each system are inputs to the class *SubExperiment*. This class instantiates the main objects (the submarine, torpedoes, decoys and jammers), and connects them to each other by the *SimEventListener* function, and the *MediatorFactory* and *Referee* classes in Simkit.

B. IMPLEMENTATION OF THE TORPEDO MODEL

The class *BasicMover* implements the interface *Mover* to model the torpedo's motion. A *BasicMover* models uniform linear motion from point A to point B.

The torpedo's actions are governed by two classes. One class, called the *TorpedoManager*, directs the initial start and search motions of the torpedo. The second class, called the *TorpedoBrain*, interprets the torpedo's tactical picture of the contacts around the torpedo at each sonar emission. The *TorpedoBrain* decides if the torpedo attacks or searches. It then directs the *TorpedoManager* to execute either the search or the next leg of the torpedo's maneuvers if it is attacking (ref Chapter III).

The torpedo's sensor is implemented in a class called *TorpedoSensor*, which models a constant rate sensor. As described in Chapter III, the model is that of a "cookie-

cutter" sensor, but with an exponentially distributed random delay of detection after an object enters the sensor's range.

The *TorpedoSensor* schedules each of the sonar emissions (the "sonar pings") which the *TorpedoBrain* "hears." The *TorpedoBrain* registers each sonar ping as it occurs; it then requests other information needed to evaluate its contacts. The class *TorpedoSonarRoom* creates and keeps a *Hashtable* list of the detected contacts. All objects in the scenario are initially detectable and are treated as contacts by the *TorpedoSensor*. The *TorpedoSonarRoom* assigns different values to each of the contacts, depending on whether the contact is a submarine, a decoy, or a jammer.

The *TorpedoBrain* copies the *TorpedoSonarRoom*'s list of contacts at each sonar ping, and begins iterating through the list. The *TorpedoBrain* first sorts the contacts into two lists: potential targets (decoy and submarine) go into a target list, and jammers into a jammer list. The two lists are then further refined to exclude invalid contacts.

One type of contact excluded is an object located outside the torpedo's sensor sector or range. The constant rate sensor used by *TorpedoSensor* detects all objects within its range. The *TorpedoBrain* evaluates whether a potential target is located within the sector of the torpedo's sensor (a symmetric area around the torpedo's heading), and removes contacts outside this area from the target list.

The *TorpedoBrain* also evaluates whether a jammer shields a potential target from the torpedo, and removes shielded targets from the target list. The *TorpedoBrain* previously received information on contacts including the jamming-radius for all jammers (instantiated from the main class). The *TorpedoBrain* then calculates whether the target is shielded by one of the jammers using the jamming-radius and the updated positions of the target and the jammers at the time of the sonar ping. The *TorpedoBrain* relates this information to the torpedo's position, which calculates the "shadow" created by the jammer. If a jammer (and its "shadow") shields a potential target from the torpedo, the contact is removed from the target list.

After excluding shielded or out-of-range contacts, the *TorpedoBrain* iterates through the target list to decide which target to attack. If the target list contains two contacts, the decoy (which has the largest target echo strength value designated by the

TorpedoSonarRoom), is attacked. If only one contact remains on the list, that target is attacked.

Finally, if the target list is empty the *TorpedoBrain* orders the torpedo to begin a new search pattern.

1. The Search Pattern

The torpedo's search pattern is implemented in the *TorpedoManager*. As discussed in Chapter III, each point in the search pattern (each of the vertices in the hexagon) is calculated on the basis of the previous direction.

2. The Chase

When the torpedo starts its chase after a target, the path of the torpedo is updated based on each sonar emission. At the time of each sonar ping, the *TorpedoBrain* class requests information about each target and directs the torpedo step by step to the target by the order *moveTo(target's position)*. The time interval between each of the sonar pings is set to one second.

3. The Classification of a Decoy

To remove the decoy from the simulation once it is detected and killed, the decoy is a subclass of the class *MortalMover*. This class allows the torpedo to "kill" the decoy when the distance between them has reached a preset minimum (20 meters). When killed, the state of the target becomes *undetectable*.

C. THE SUBMARINE MODEL

Two classes, *SubmarineManager* and *SubmarineBrain* govern the submarine. For each run the submarine will be started with an initial velocity which direction is defined by the main class to be (-1, 0). The main class positions the submarine in its initial position (0, 0), and orders it to move to the position (-2000, 0) by the order *moveTo* in the class *SubmarineManager*.

All of the later actions executed by the submarine are implemented by the class *SubmarineBrain* in the model. *SubmarineBrain* calculates in which of the quadrants around the submarine (ref Section II.B.4) the torpedo is located. It then decides to send

the decoy to Quadrant I or IV and to turn the submarine into Quadrant III or II, respectively.

1. The Execution of the Torpedo Countermeasures

The *SubmarineBrain* calculates the course of the decoy on the basis of the bearing of the torpedo. It calculates the end position of the decoy, and schedules the time to launch the decoy. The *SubmarineBrain* also calculates the course and end position of each of the jammers on the basis of the submarine's course and launch position. Both the decoy and the jammers, which are of the class *Target*, are sequentially instantiated by the *SubmarineBrain* before it launches them.

2. The Evasion by the Submarine

The submarine's evasive maneuvers, turning away from its decoy and accelerating, are both implemented in the class *SubmarineManager.* The class *BasicMover*, which models linear motion, positions the submarine. *SubmarineManager* subdivides the submarine's turn into linear segments by small instant shifts of direction. Each turn begins with a 7.5-degree change in direction (θ_1 in Figure 8), maintains 15-degree shifts, and continues turning until the last shift of 15 or fewer degrees. Each of these turn segments follows a circular path so that the submarine maintains its preset turn radius. At each shift of direction the *SubmarineManager* calculates the coordinates of the next vertex of the path on the basis of the previous leg's direction and by a shift of basis into the standard coordinate system of the model. The order *moveTo(next position)* directs the submarine into its new position.

The submarine's acceleration during the turn is implement in the model by the *SubmarineManager. SubmarineManager* calculates the time the submarine uses to get to the next vertex of the path at constant acceleration. On that basis it calculates and orders an average speed for the next leg.

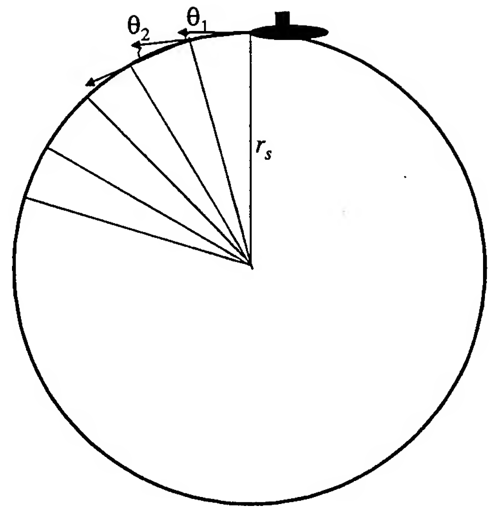

Figure 8: The turn segments of the submarine.

The *SubmarineManager* also calculates the submarine's acceleration during the submarine's linear motion. In these cases *SubmarineManager* divides the submarine's path in segments of 10 seconds time intervals, and calculates and orders an average speed for each segment.

D. THE TORPEDO COUNTERMEASURE MODEL

The two basic elements of the submarine's torpedo countermeasure system, the decoy and the jammers, are implemented in the class *Target*, an extension of *MortalMover*. *SubmarineBrain* models the behavior of the decoy and jammers, and executes them. *TorpedoBrain* models the way the torpedo evaluates its targets.

1. The Decoy

The *SubmarineBrain* fires the decoy by instantiating it (naming it "Decoy,") in the *Target* class, and starting it on its course calculated by the *SubmarineBrain*. *SubmarineBrain* orders the decoy using the *moveTo* command to a position 10,000 meters from the submarine. The motion of the decoy is then modeled as a *BasicMover*.

2. The Jammers

The four jammers, or noisemakers, are also of the class *Target* and are instantiated sequentially by the *SubmarineBrain*. As with the decoy, *BasicMover* models the motion of the jammers. As described above, *TorpedoBrain* uses the jamming radius to determine if the jammer shields the target from the torpedo in its current position.

This chapter described how the simulation program models each of the elements and their interaction. The next chapter describes the design of the experiment and presents the analysis of the results.

V. THE DESIGN OF THE EXPERIMENT AND THE ANALYSIS OF THE RESULTS

This chapter describes the design of the simulation experiment, presents output data, and analyzes the results. Outcomes are based on the measure of effectiveness (MOE) defined in Chapter II. This MOE is the probability that the incoming torpedo does not catch the submarine, based on the maximum speed of the submarine (ref Chapter II, p 7). The design of the experiment is based on this MOE.

A. THE DESIGN OF THE EXPERIMENT

The design of the experiment provides results on the ability of the submarine to evade torpedoes at varying speeds. The parameters expected to influence the outcome of each run (i.e., does the torpedo catch the submarine or not) are the initial speed of the submarine, the maximum speed of the submarine, and the start position of the torpedo.

The experiment chosen is of robust design, where the start position of the torpedo is fixed at given positions. In reality, the drop position of the torpedo relative to the submarine is an uncontrollable factor for the submarine. The experiment treats uncontrollable factors as sources of noise (ref Sanchez *et al.* 1998). The design point provides an estimate of mean performance and of the uncontrolled variability.

The experiments cover all four quadrants and both sides of the submarine, but are not symmetric on each side of the submarine. The torpedo conducts its search pattern by circling counter-clockwise, thus the torpedo always turns left when it begins its search. The experimental drop positions of the torpedo are divided into four bearings, one in each quadrant, and two distances, one close and one further out (ref Figure 9). The close drop positions are approximately 500 meters and the longer distance drop positions approximately 1400 meters from the submarine. The experiment is thus based on these eight different torpedo start positions.

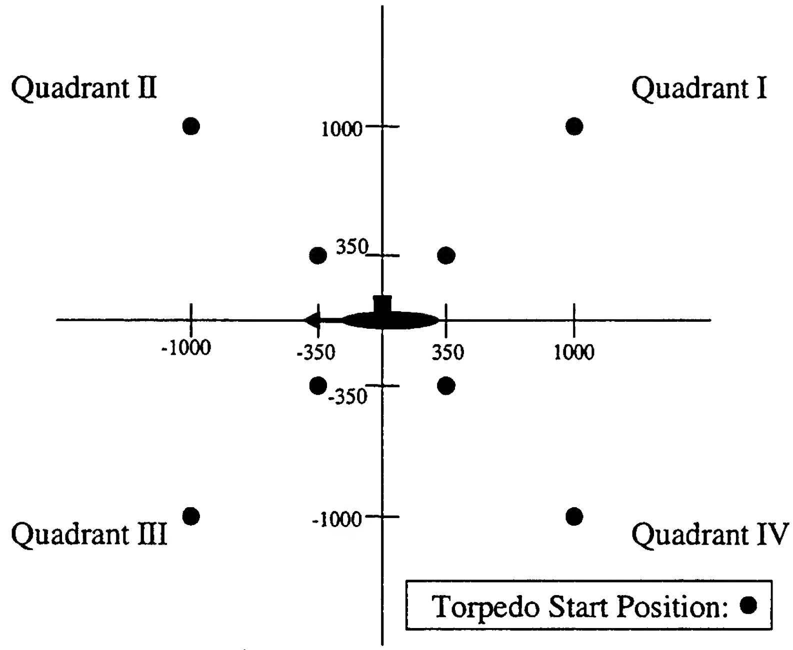

Figure 9: The eight start positions of the torpedo.

The initial speed of the submarine does not vary throughout the experiment, while the maximum speed of the submarine varies. A conventional submarine normally cruises at speeds between two knots and six knots and in most cases maintains a speed between three and ten when it is attacking. The initial speed of the submarine is five knots during the experiment, since that speed is regarded as a likely average speed.

Three maximum speeds, one low, one medium, and one high are used in the initial part of the experiment. They have been chosen to establish whether the relationship between the probability of survival and the maximum speed of the submarine is linear, and to identify a range of speeds to be investigated further. The three maximum speeds tested in the initial part of the experiment are 12 knots, 18 knots and 25 knots. A maximum speed of 12 knots is an extremely low maximum speed for a submarine, 25 knots is a very high speed for a conventional submarine, and 18 knots is a common maximum speed in today's submarine designs (ref Chapter II).

The eight start positions of the torpedo and three maximum speeds of the submarine give a total of 24 configurations or design points. Each of these design points can be run for a specific number of iterations. The variability of each iteration within

each configuration is provided by the random time delays of the constant rate sensors of both the torpedo and the submarine, and by the random time delay of the firing of each countermeasure element. Fifty iterations are run for each design point using common random numbers (ref Law and Kelton, 1991) for the sensor detection times and the launch times of the countermeasure system. Based on the runs from the first 24 design points, new design points are identified for the next set of simulations. The outcome of the experiments is the probability of survival of the submarine based on the number of times the submarine was caught by the torpedo for each design point and maximum speed parameter.

The next section presents the results from the initial experiment and analyzes these results.

B. THE OUTCOME OF THE SIMULATION OF THE FIRST SET OF DESIGN POINTS

As described in the previous section, the first set of simulation experiments consists of 24 design points (eight torpedo drop positions times three maximum speeds) with 50 replications at each design point. The results show that the submarine is killed in every one of the runs where the torpedo starts at the closest range (ref Table 1) regardless of the maximum speed of the submarine. These results also show that the probability of survival (P_s) for a submarine with maximum speed 12 is zero.

		Speed	
Torpedo Start Position	12 kt	18 kt	25 kt
Short dist, Quadrant 1	0	0	0
Short dist, Quadrant 2	0	0	0
Short dist, Quadrant 3	0	0	0
Short dist, Quadrant 4	0	0	0
Long dist, Quadrant 1	0	0.6	0.6
Long dist, Quadrant 2	0	0.58	0.58
Long dist, Quadrant 3	0	0.24	0.24
Long dist, Quadrant 4	0	0.32	0.32

Table 1: Probability of survival of the submarine at varying maximum speeds and drop positions of the torpedo.

Because the probability of survival is zero for all the runs in which the torpedo is dropped at a close distance, the data based on design points using close distances are not analyzed further, nor are such design point investigated in additional simulation runs.

The asymmetry between the results from Quadrant I and II versus Quadrant III and IV is surprising, but might be explained by the search pattern of the torpedo which always turns counter-clockwise. Although it is not the focus of this thesis to analyze the survivability of the submarine as a function of the direction from which an attack comes (other than the design points previously mentioned), a caution about the interpretation of results must be stated. The initial experiments and probabilities for survival generated show different results among the quadrants. As noted above, no symmetry among runs from different quadrants is expected due to the counter clockwise search pattern of the torpedo. It is difficult to explain, however, why the difference between Quadrants I and II, and Quadrants III and IV, are so large. Perhaps the answer lies in the search pattern of the torpedo. When the torpedo starts in either the first or second quadrant, it by default turns left towards the decoy. The opposite situation occurs in the third and fourth quadrants where the torpedo turns away from the decoy during its first left turn. The torpedo's behavior is the only source of asymmetry in these scenarios, so it is logical that this is the cause of the asymmetry in the results.

When investigating design points representing the long distance torpedo drop positions (1400 meters), two results are of interest. Firstly, the probability of survival is always zero for the slow (12 knot) submarine. Secondly, the probabilities of survival for the 18-knot and 25-knot submarines in each of the quadrants are equal. (ref Table 2).

In order to find the relationship between maximum speed and the probability of survival, the results from each of the quadrants are pooled into one probability measure for each maximum speed. These pooled results with a 95% confidence interval, are shown in Figure 10.

Quadrant	Position	Sub Speed	P(survival)	P(kill)	# of kills
1	(1000.00, 1000.00)	12	0	1	50
1	(1000.00, 1000.00)	18	0.6	0.4	20
1	(1000.00, 1000.00)	25	0.6	0.4	20
2	(-1000.00, 1000.00)	12	0	1	50
2	(-1000.00, 1000.00)	18	0.58	0.42	21
2	(-1000.00, 1000.00)	25	0.58	0.42	21
3	(-1000.00, -1000.00)	12	0	1	50
3	(-1000.00, -1000.00)	18	0.24	0.76	38
3	(-1000.00, -1000.00)	25	0.24	0.76	38
4	(1000.00, -1000.00)	12	0	1	50
4	(1000.00, -1000.00)	18	0.32	0.68	34
4	(1000.00, -1000.00)	25	0.32	0.68	34

Table 2: Results from the simulations where the torpedo started at the long distance.

The result from the 12-knot submarine is obviously the worst of these results; the probability of being killed is certain with zero variance. At this stage it can be concluded that a submarine designed with a maximum speed of 18 knots has a higher probability of survival than one with 12 knots.

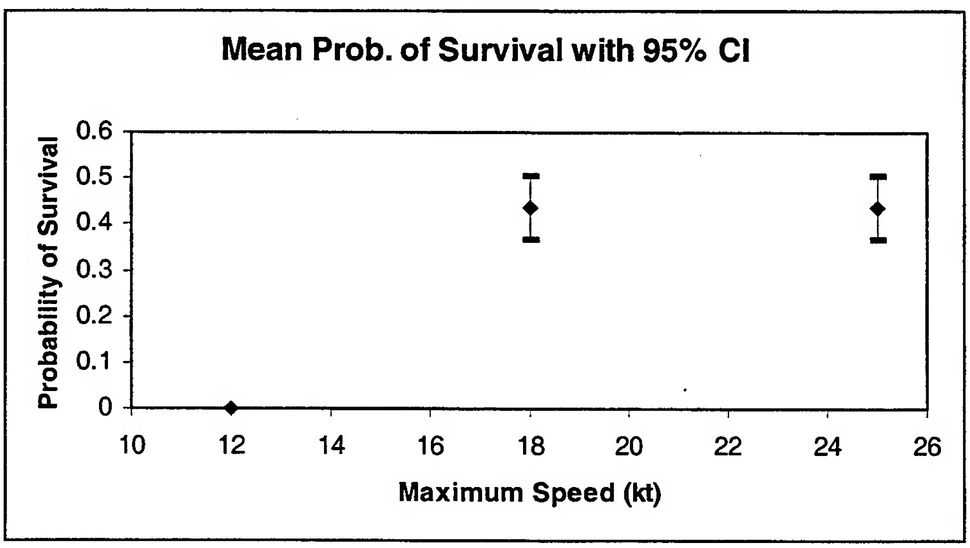

Figure 10: Results from the simulations where the torpedo started at the long distance.

The relationship between speed and the probability of survival for submarine's with 18 and 25 knot maximum speeds is identical. Although maximum speeds above 25 knots are nearly impossible for conventional submarines, it is still of interest to see how

this model functions for higher maximum speeds. Specifically, will survivability remain constant or rise with greater maximum speed?

Also, the initial experiment does not show how the probability of survival increases between 12 and 18 knots. Further simulation runs therefore investigate maximum speeds between 12 and 18 knots and test how the model performs for maximum speeds above 25 knots.

C. THE OUTCOME OF THE SIMULATION WITH ADDITIONAL SETS OF DESIGN POINTS

This experiment investigates design points using speeds of 13, 14, 15, 16, and 17 knots at each of the four long drop positions. A maximum speed of 30 knots is also simulated at four drop positions. The analysis of these additional data and elements of the data from the previous section follow.

1. Analysis of the Extended Experiment

The results from the extended experiment show the relationship between the probability of survival and maximum speed with respect to each of the quadrants the torpedo is dropped in (ref Figure 11).

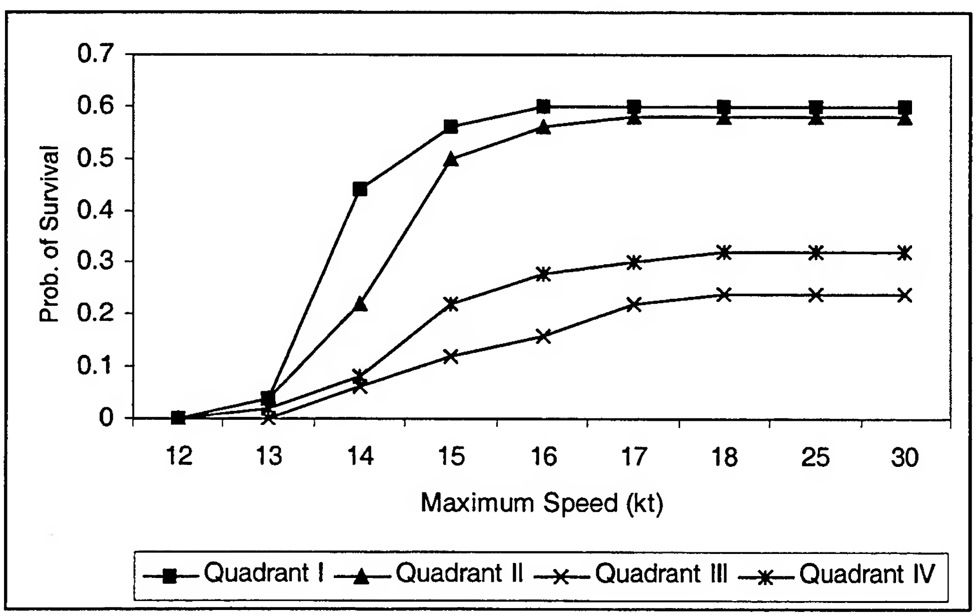

Figure 11: Probability of survival versus speed for each of the quadrants.

The graph shows that if the torpedo is dropped in Quadrant I or II, the probability of survival is much greater than if dropped in the two other quadrants. This fact was also shown in the initial experiment. Secondly, the graph shows that for Quadrants I and II the best probability is met at a lower maximum speed than for Quadrants III and IV. In the 13 to 18 knots range the slope is higher for Quadrants I and II than for Quadrants III and IV. However at maximum speed of 18 knots or greater the maximum probability of survival is achieved in all quadrants. Furthermore the probability of survival stays constant for all the quadrants for maximum speeds above 18 knots.

While the differences in the survival probabilities among the four quadrants are interesting from a tactical point of view, they are not the main focus of this thesis. The designed maximum speed of the submarine should result in good surviving probabilities regardless of the torpedo's bearing. Therefore the data are pooled into one set of data for each maximum speed in order to analyze survival probabilities across all quadrants.

The pooled data set for each incremental maximum speed from 12 to 30 knots are shown in Figure 12. The graph shows that the confidence interval of the probability of survival increases as the maximum speed increases from 12 to 18 knots. At 12 knots the probability of survival is zero without any variability at all. When the maximum speed increases towards 18 knots the confidence intervals show that the variability also increases.

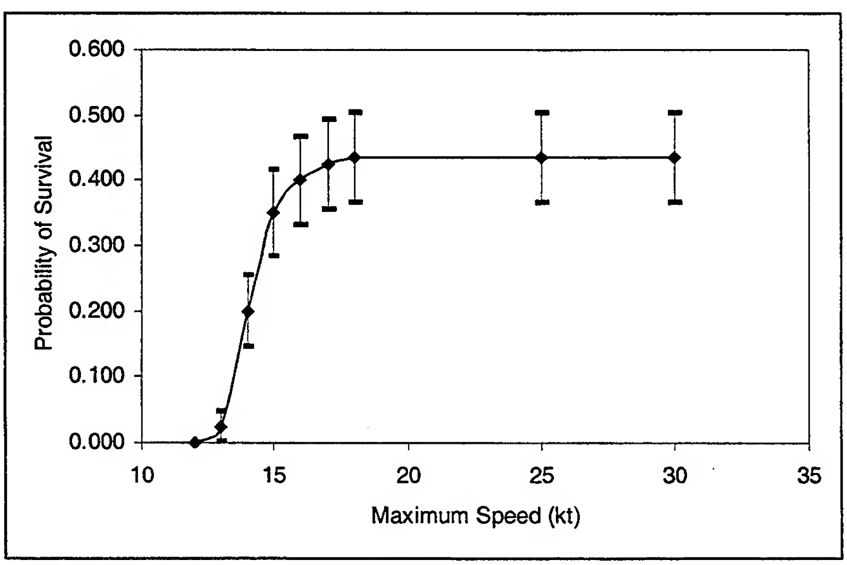

Figure 12: Mean survival probabilities with 95% confidence intervals.

In order to understand the relationship between survival probability and speed better the data curve was fit to a three parameter logistic regression model. This model hypothesizes an equation of the form

$$\overline{Ps} = \frac{\beta_1}{1 + \exp(-\beta_2(MaxSpeed - \beta_3))}$$

where $\overline{Ps}$ is the mean probability of survival. Using the data set resulting from the simulation, the β's are estimated as: $\beta_1 = 0.43$, $\beta_2 = 1.90$, and $\beta_3 = 14.14$. This estimation was performed by the statistical package S-Plus. The curve that best approximates the data under this model can therefore be expressed as follows:

$$\overline{Ps} = \frac{0.43}{1 + \exp(-1.90(MaxSpeed - 14.14))}.$$

Figure 13 shows how the equation approximates the data points from the simulation.

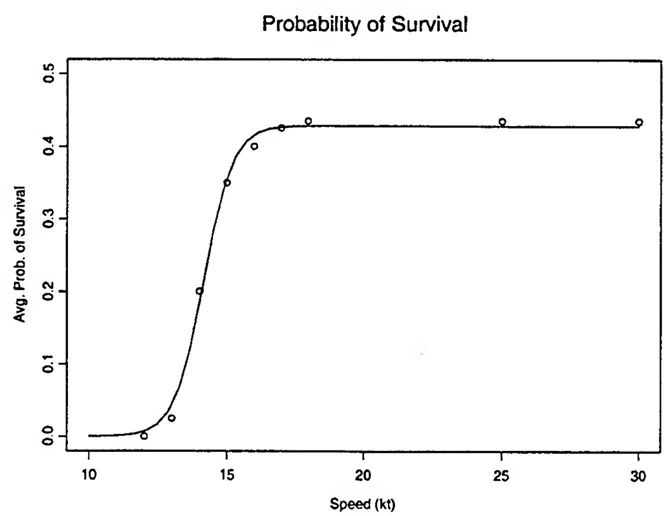

Figure 13: The curve of the three parameter logistic equation and the scatter plot of the probability of survival data versus maximum speed.

The parameter β_1 represents the asymptotic upper limit of the curve, while β_3 represents the turning point. The parameter β_2 together with β_1 and β_3 describes the slope of the curve as follows:

$$\frac{dy}{dx}=\frac{\beta_1\beta_2(\exp(-\beta_2(x-\beta_3)))}{(1+\exp(-\beta_2(x-\beta_3)))^2}.$$

For example at a speed that gives the maximum slope at the turning point β_3 the slope is

$$\frac{dy}{dx}=\frac{\beta_1\beta_2}{4}.$$

For these values the equation gives a slope of 0.203 when the maximum speed is 14.14 knots.

This estimation provided an equation describing the relationship between the probability of survival of the submarine and its maximum speed. The following section describes how the results from the simulation and the survivability curve are interpreted.

2. Interpretation of the Results

The conventional view from WWI and WWII that more speed is better has been confirmed in the speed range from 12 to 18 knots. This is clearly shown with the use of the type of countermeasures used in this model. Without more effective countermeasures maximum speeds below 18 knots should not be considered.

The fact that the probability of survival does not increase for maximum speeds above 18 knots is quite surprising however. One would have thought that the probability of survival would increase as the maximum speed increases. One possible explanation of the results for maximum speeds above 18 knots is as follows. The faster speeds are not sufficient to carry the submarine out of the torpedo's range for those scenarios in which the torpedo acquires the submarine. At that point it becomes a race that the torpedo always wins. Therefore faster speeds do not help the submarine in those scenarios.

The time at which the torpedo gains contact with the submarine after the investigation of the decoy is done depends on the relative position of the jammers, the submarine, and the torpedo. If the submarine emerges into the line of sight of the torpedo, it will have to be within the torpedo's sensor range for the torpedo to acquire. Since the initial geometry in each run is identical for each maximum speed in the experiment, the distance between the torpedo and the submarine when detection takes place is a function of the submarine's maximum speed. However the increased distances

are not sufficient for the submarine to escape in those cases. The randomness build into the model will allow a certain proportion of the submarines to enter the torpedo's sensor range at a time when the torpedo is not directing its sensor towards the submarine. If the submarine has sufficient speed it will manage to get outside the torpedo's sensor range by the time the torpedo has done one turn of its search and is directing the sensor towards the submarine. A slow submarine will not manage that. A certain proportion of the submarines will not manage to get out of the torpedo's sensor range however high its maximum speed is.

In light of the relationship between the probability of survival of the submarine and its maximum speed, it is of importance to revisit the assumptions of the model and the design of the experiment. Although all factors were described in earlier chapters, two of the most important ones are highlighted here.

The initial speed of the submarine was five knots for all the experimental runs. That parameter may vary widely in real situations. It is not, for example, the worst case imaginable, where the submarine is dead-in-water. In such a case, the submarine must accelerate for a longer time before it reaches its maximum speed, giving the torpedo much more time to catch it.

The jammers are modeled in this thesis as "cookie-cutter" noisemakers, which are 100% efficient within a specific radius. A real jammer could possibly be 100% efficient against a torpedo sonar within a jamming radius, but could also have a reduced effect outside that radius. Two or more jammers might overlap so that the combined area forms a unified 100% efficient wall of sound against the torpedo sonar. The radius of each of the jammers might also in reality have a different radius than what is modeled here. The radius could possibly change from location to location or from day to day, depending on the oceanographic conditions and the acoustic conditions of the surrounding water.

How would changes to the assumptions of initial speed and jammer efficiency influence the probability of survival curve? Perhaps the upper asymptotic limit of the curve might be lowered, so that the probability of survival decreases for the high maximum speed range. Additionally, the entire curve might be shifted to the right,

suggesting that the highest probability of survival occurs at maximum speeds greater than 18 knots.

The probability of survival curve generated has two distinct segments. Between 12 and 18 knots, survivability varies widely as a function of maximum speed. A small change in maximum speed within this range leads to a large change in the survivability of the submarine. In the second segment (between 18 and 30 knots), the curve flattens out. Increasing maximum speed does not improve the submarine's probability of survival.

To design a submarine with a high probability of surviving torpedo attacks, this study suggests that the submarine should be capable of reaching maximum speeds equal to those in the upper (flat) segment of the curve. This study does not suggest what the actual maximum speeds should be because the curve generated depends on the specific assumptions described in previous chapters. For a real system not restricted by the assumptions made here, the curve might have a different shape, or it may have similar shape but be shifted in one direction. Figure 14 shows an example of the latter situation, where the curve is shifted two knots to the right. In this example, a 20 knot maximum speed (rather than 18) provides the highest probability of survival, and the probability of survival for 16 knots falls by half, from 0.4 to 0.2.

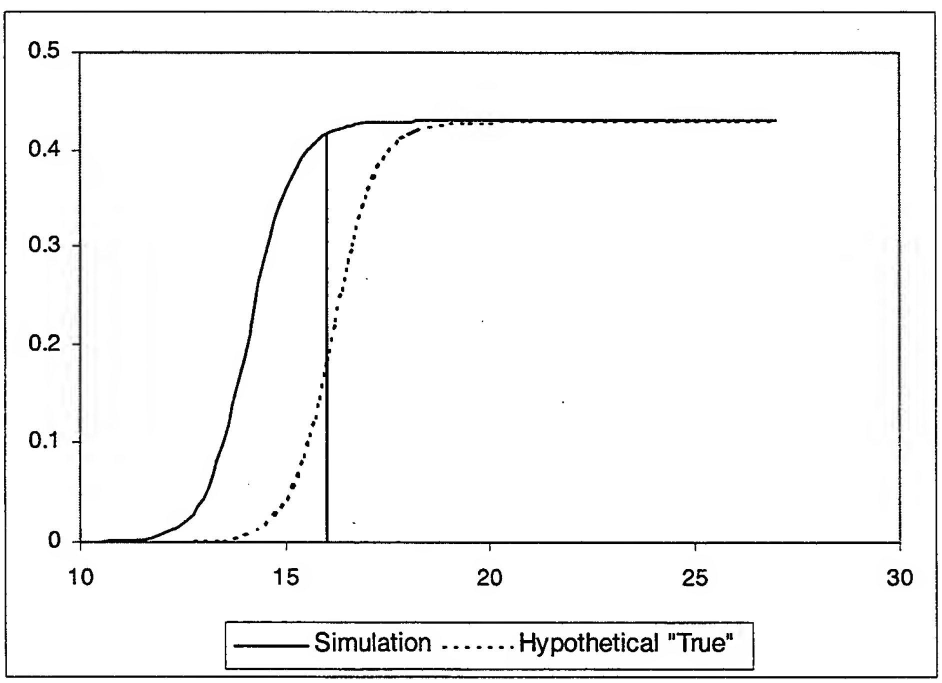

Figure 14: A shift of the curve of two knots to the right.

This example emphasizes how important it is to design a submarine with maximum speeds well into the upper flat area of the curve. As this example shows, incremental changes in maximum speed until the point where the curve flattens may result in large increases in survival probability.

The final chapter concludes these thoughts and makes recommendations based on these findings.

VI. CONCLUDING REMARKS

This thesis has examined the threat to a conventional submarine from a modern light torpedo dropped from a ship's helicopters or from maritime patrol aircraft (MPA). It simulates the interaction between the submarine, the torpedo, and countermeasure systems to determine the effect of speed on the submarine's evasive performance. Results of the simulation provide information to the submarine community on the probability of submarine survival for a range of maximum speeds. This chapter summarizes the major findings and conclusions of the study, and makes recommendations for submarine maximum speed. The final section makes suggestions for further research.

A. CONCLUSIONS AND RECOMMENDATIONS

The intent of this thesis was to find the relationship between maximum speed of a conventional coastal submarine and the evasive capability of the submarine. In the first chapter the problem is stated in two questions:

- What is the effect of a conventional submarine's maximum speed on its evasive performance when attacked by a modern light ASW torpedo?

- What should be the maximum speed of a conventional coastal submarine equipped with a torpedo countermeasure system be to ensure a specified probability of survival while evading a light ASW torpedo?

The simulation and analysis of the results show that a relationship exists between an evasive performance of a submarine and its maximum speed. Under the assumptions of this study, a submarine with maximum speed below 12 knots cannot evade a torpedo. The probability of survival for the submarine improves with each incremental increase in maximum speed 12 to 18 knots. According to this analysis, speeds above 18 knots do not improve the submarine's probability of survival. The conclusion is that the submarine's maximum speed affects its evasive performance within a specific range. Although the model simulated shows improvements only in the range between 12 and 18 knots, a real system might exhibit improvements across a different range.

The estimated equation found in the previous chapter (ref page 42), expresses the characteristics of the simulation, which is only a model of reality. The data for the model come from open sources and so the particular numbers do not necessarily represent the behavior of actual submarines and torpedoes. However, the shape of the curve is likely to be realistic.

With respect to probability of survival while evading a light ASW torpedo, the maximum submarine speed providing the greatest probability of survival (0.435) is 18 knots. The model is based on assumptions that might make the results more favorable for the modeled submarine than in a real life situation. This study suggests at least a maximum speed of 18 knots with higher speed capability recommended, and points out that interpretations of the survival curve in the range around 18 knots must be made with care. Again, a real system not operating under the same assumptions as this model might show different probabilities of survival at different speeds.

It should be kept in mind that these results come from an experiment where the torpedo is dropped at a distance from the submarine of approximately 1400 meters. When dropped at the closest distance (500 meters) the modeled submarine had a probability of survival of zero, regardless of its maximum speed.

B. SUGGESTIONS FOR FURTHER WORK

Changes in the assumptions of the model may change the shape or range of the probability of survival curve and the conclusions regarding maximum speed. From this study, there is some reason to believe that changes in the initial speed of the submarine in particular could lead to changes in the submarine's probability of survival. These issues bear for further investigation.

The upper flat part of this model's survival curve (between 18 and 30 knots) should also be investigated further. Is it true that a submarine with a maximum speed of 30 knots does not survive any better than a submarine with a maximum speed of 18 knots? One way to investigate this question might be to choose an MOE that focuses on the submarines that are killed, but emphasizes the length of time before it is killed. Models with different maximum speeds can, as this thesis shows, have the same

probability of survival. A question to ask would be, for the submarines that were killed, are the times to kill equal for submarines with different maximum speeds? If not then perhaps higher maximum speed gives the submarine more time to execute new or other types of evasive actions and to survive.

This work can also be extended to further investigate countermeasure systems. Is the configuration of one decoy and four jammers a good configuration? Are there other more efficient ways to deploy each of the elements of the countermeasure system geometrically around the submarine? This thesis partially answers some questions but suggests many others deserving further investigation.

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LIST OF REFERENCES

Law, A., and W. D. Kelton, *Simulation Modeling and Analysis*, Second Edition, Mc Graw Hill, 1991

Miller, D., *Submarines of the World,* Salamander Books Ltd, 1991

Sanchez, S. M., P. J. Sanchez, and J. S. Ramberg, "A Simulation Framework for Robust System Design", Chapter 12, pp 279 – 314, *Concurrent Design of Products, Manufacturing Processes and Systems,* ed. Wang, B., Gordon and Breach, N.Y., 1998.

Stork, K.: *Sensors on object oriented discrete event simuation*, Masters Thesis, Operations Research Department, Naval Postgraduate School, Monterey, CA, 1996.

Watts, Anthony J., *Jane's Underwater Warfare Systems, Eleventh Edition, 1999-2000,* Jane's Information Group Limited, UK, 1999

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